Lecture 11

Microwave Measurement Techniques

A. Nassiri – ANL

June 19, 2003

Introduction

• Measurement rules, difficulty in voltage and current measurements, test equipment

Noise

Noise power, S/N, noise figure, equivalent noise temperature, noise figure of a cascaded circuit

Frequency measurements

Frequency counter method, wavelength measurement method, wavemeter method

Detection devices

Thermistor, barretter, thermocouple, crystal detector

Power measurements

Thermistor power meter, arrangements for low, medium and high power measurement

Attenuation measurements

Insertion loss, substitution method

VSWR measurements

Introduction to S-parameters

Reasons to use S-parameter, definition, signal flow graph, Properties

Microwave test equipment analyzers

Purpose and operating principle of spectrum analyzer and network analyzer

Introduction

1. Rules of a "correct microwave" measurement

(a) know what parameters you want tested.
(b) have a proper test arrangement. "Always check the power handling capacity of your microwave components and test equipment."
(c) know how to perform your test.
(d) know how to interpret the results.

→ *Plan ahead.*

No calibrated, do not use for quantitative data.

2. Difficult or impossible in the measurement of voltage and current at microwave frequencies because

(a) voltage and current readings vary with position along the transmission line,
(b) voltage and current are difficult to define in non-TEM transmission lines.

3. Test equipment

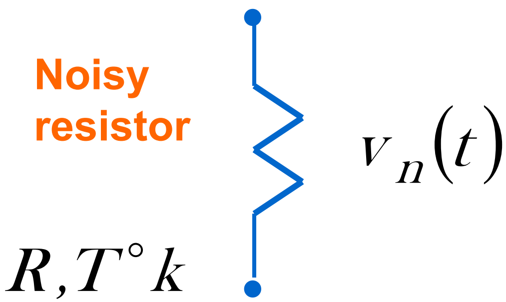
(a) sources: sweeper (YIG tuned oscillator), synthesizer, klystron oscillator, Gunn oscillator, ...

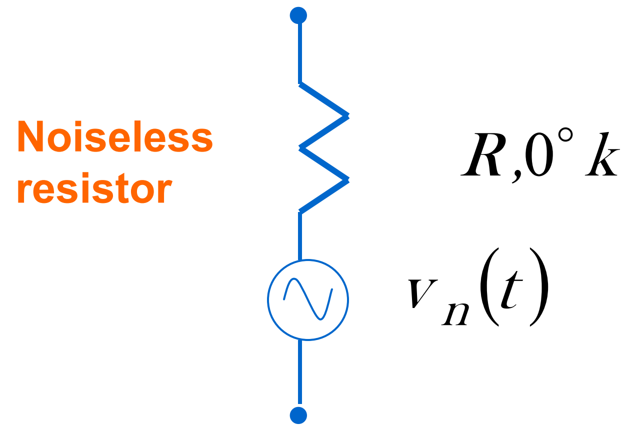
(b) receivers: power meter, spectrum analyzer, network analyzer, detector, frequency counter, wavemeter, noise figure meter, …

(c) auxiliary devices:
attenuator, directional coupler, slotted line, coaxial cable, adapter, antenna,…

Noise

Noise power (due to thermal noise)





Planck's black body radiation law,

rms voltage across a resistor R is

$$\text{v}_n = \sqrt{4kT \int \frac{hf/kT}{e^{hf/kT} - 1} R(f)\,df}$$

$hf << kT$ **at microwave frequencies** $\longrightarrow$

$$e^{hf/kT} - 1 \cong \frac{hf}{kT} \;\rightarrow\; \text{v}_n = \sqrt{4kTBR}$$

$$P_n = \left(\frac{\nu_n}{2R}\right) R = \frac{\nu_n^2}{4R} = kTB$$

The maximum power delivered from the noisy resistor is $P_n = kTB$, which is considered equally across an entire microwave band.

A resistor temperature at 300^0 k, noise power for a 10kHz bandwidth receiver → $P_n = 4.14 \times 10^{-17}$ W = -176dBW= -146dBm

At the standard temperature of 290^0 k, the noise power available from a lossy passive network in a 1Hz bandwidth is -174dBm/Hz.

Signal-to-noise ratio (SNR)

$$\left.\frac{S}{N}\right|_{dB} = 10\,log\,\frac{P_s}{P_n}$$

Difficult to measure

$$\left.\frac{S+N}{N}\right|_{dB} = 10\,log\,\frac{P_s + P_n}{P_n}$$

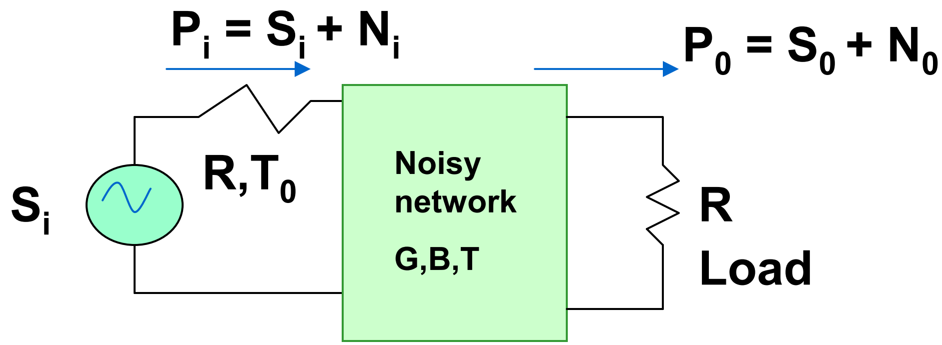
Measurable quantity

A receiver produces a noise power of 200mW without signal, as signal is applied, the output level becomes 5W.

$$\left.\frac{S+N}{N}\right|_{dB} = 10\,log\,\frac{P_s + P_n}{P_n} = 10\,log\,\frac{5}{0.2} = 14dB$$

Noise figure

A figure of merit to measure the degradation of SNR of a system



$$NF = \frac{(S/N)_i}{(S/N)_o} \geq 1 \qquad NF_{dB} = 10\,log\,NF \geq 0dB$$

For a passive device with G=1/L and in thermal equilibrium at the temperature T, $N_0 = kTB = N_i$, $S_o = GS_i$,

$$NF = \frac{(S/N)_i}{(S/N)_o} = \frac{S_0}{S_i}\frac{N_i}{N_o} = L$$

An amplifier with input signal 100μW and the noise power is 1μW. The amplified signal is 1W with noise power 30mW.

$$signal\ \ gain = 10\,log\,\frac{1000000}{100} = 40dB$$

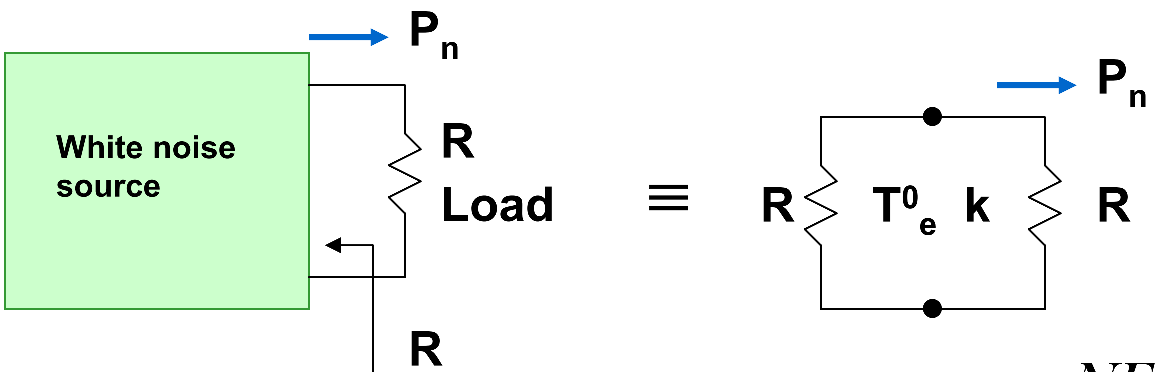
$$noise\ \ gain = 10\,log\,\frac{30000}{1} = 44.7dB > 40dB$$

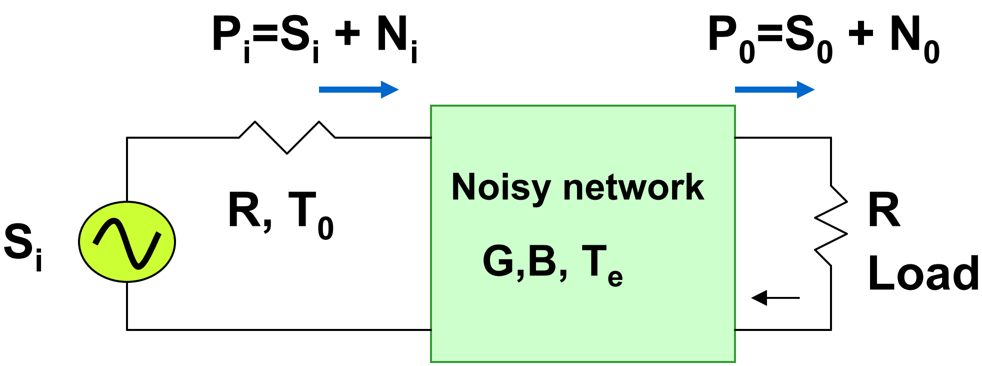
$$NF = \frac{(S/N)_i}{(S/N)_o} = \frac{100/1}{1000/30} = 3 > 1 \qquad NF_{dB} = 4.7dB > 0dB$$

An amplifier with NF 6dB has an input SNR=40dB,

$$NF = \frac{(S/N)_i}{(S/N)_o} \rightarrow \left.\frac{S}{N_o}\right|_{dB} = \left.\frac{S}{N_i}\right|_{dB} - NF_{dB} = 40 - 6 = 34dB$$

Equivalent noise temperature: the absolute temperature to generate the same noise power, not the physical temperature of the device equivalent noise temperature $T_e \equiv P_n / kB$





$$NF = \frac{(S/N)_i}{(S/N)_o}$$

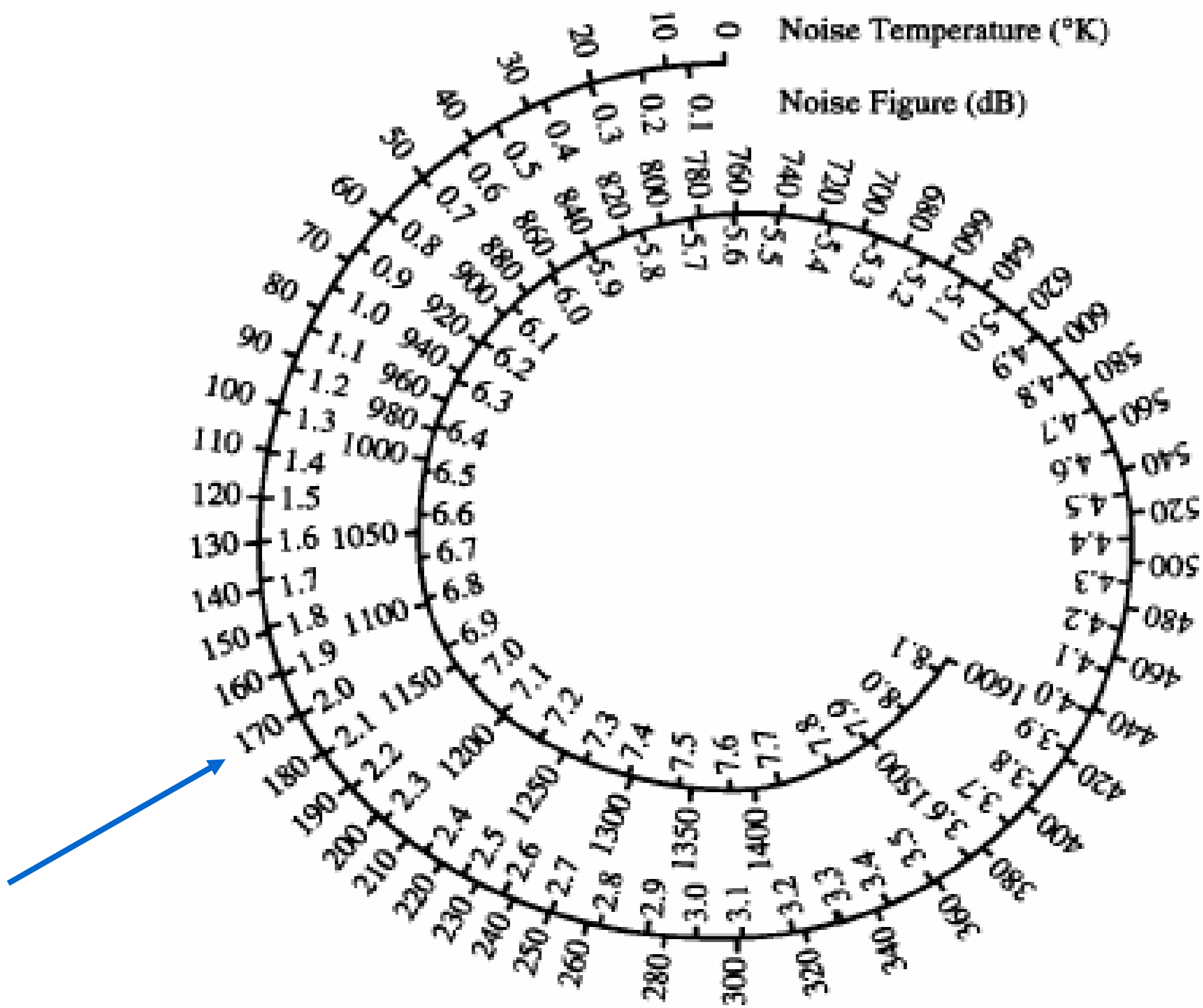
$$= \frac{S_i}{kT_0B}\frac{Gk(T_0+T_e)}{GS_i}B$$

$$= 1 + \frac{T_e}{T_0} \geq 1$$

$$\rightarrow T_e = (NF-1)T_0$$

Example:

A LNA (low noise amplifier) NF =2dB =1.585 $\rightarrow T_0$ = (NF-1)T=170^0 K



NF of a cascaded circuit

$$NF = \frac{(S/N)_i}{(S/N)_o} = \frac{S_i}{S_0}\frac{N_0}{N_i}$$

$$= \frac{1}{\prod_{i=1}^{N} G_i}\left\{\frac{kT_0B\prod_{i=1}^{N}G_i}{kT_0B} + \frac{k(NF_1-1)T_0B\prod_{i=1}^{N}G_i}{kT_0B}\right.$$

$$\left. + \frac{k(NF_2-1)T_0B\prod_{i=2}^{N}G_i}{kT_0B} + \cdots + \frac{k(NF_N-1)T_0BG_n}{kT_0B}\right\}$$

A three-stage amplifier

Stage	power gain		noise figure	
1	10	10dB	2	3dB
2	20	13dB	4	6dB
3	30	14.8dB	6	7.8dB

Total gain=6000=37.8dB

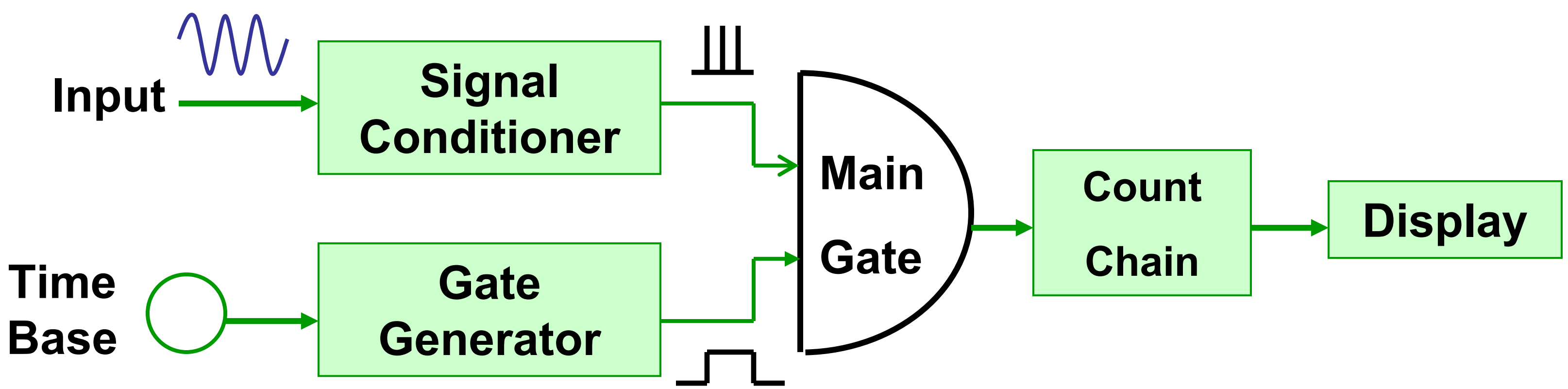
Total NF=2+[(4-1)/10]+[(6-1)/(10×20)]=2.325=3.66dB

Frequency measurements

Two approaches: using frequency counter to measure frequency directly, and using probe to measure the wavelength in a transmission line.

Frequency counter approach

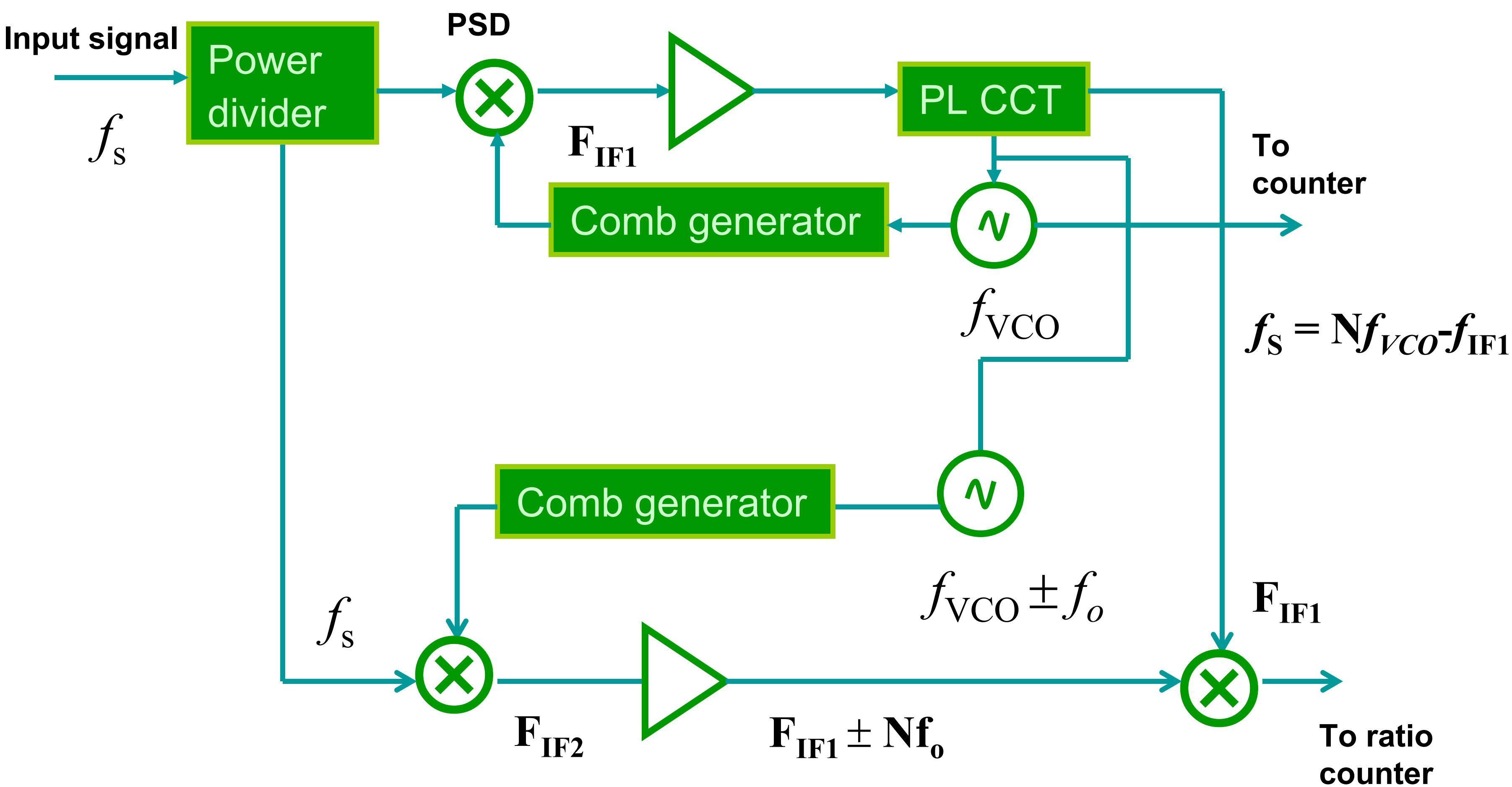
(1) Basic principle: direct counting <500MHz



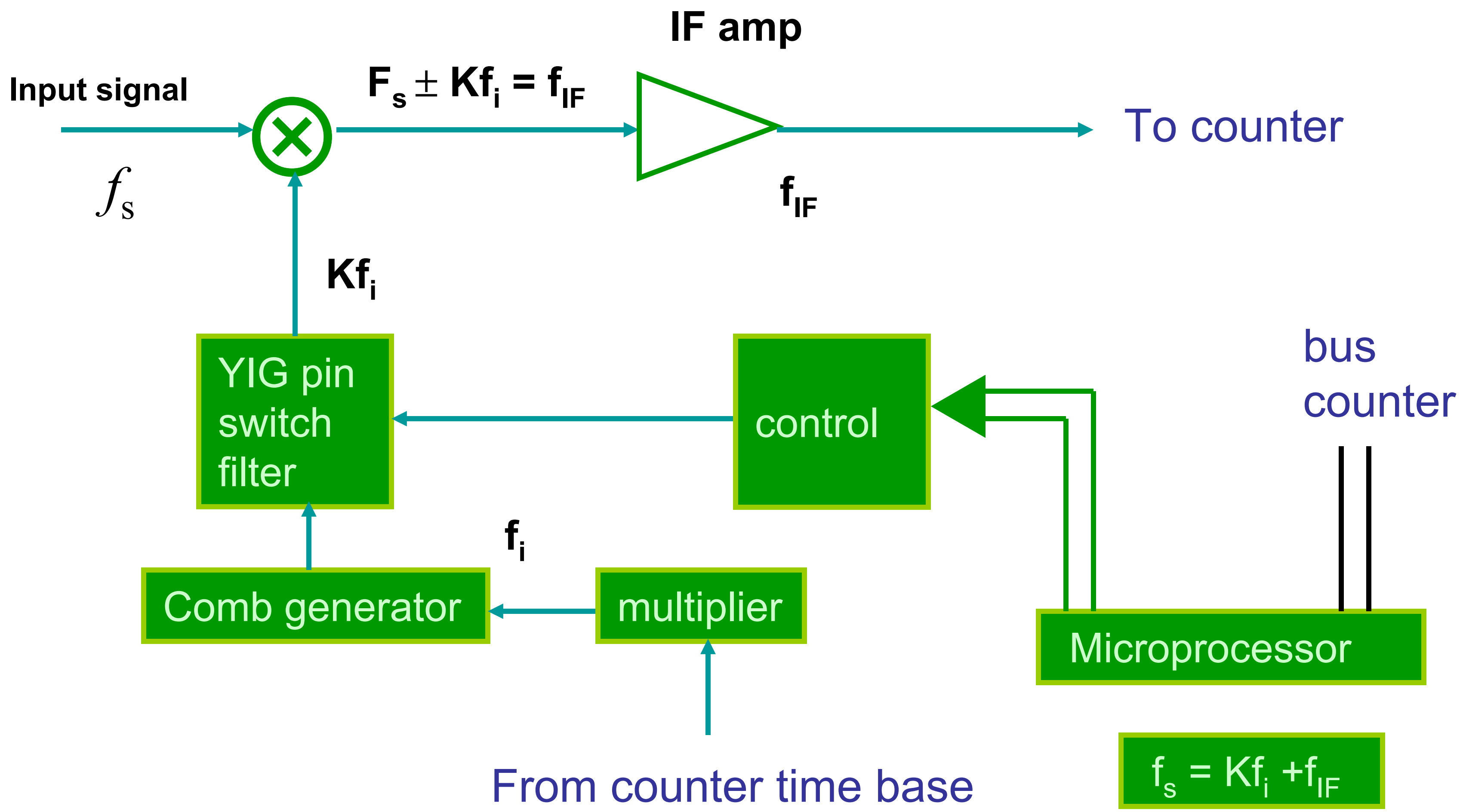
(2) Using frequency down-conversion techniques for microwave signals

- **Pre-scaling: divider circuit <2GHz**

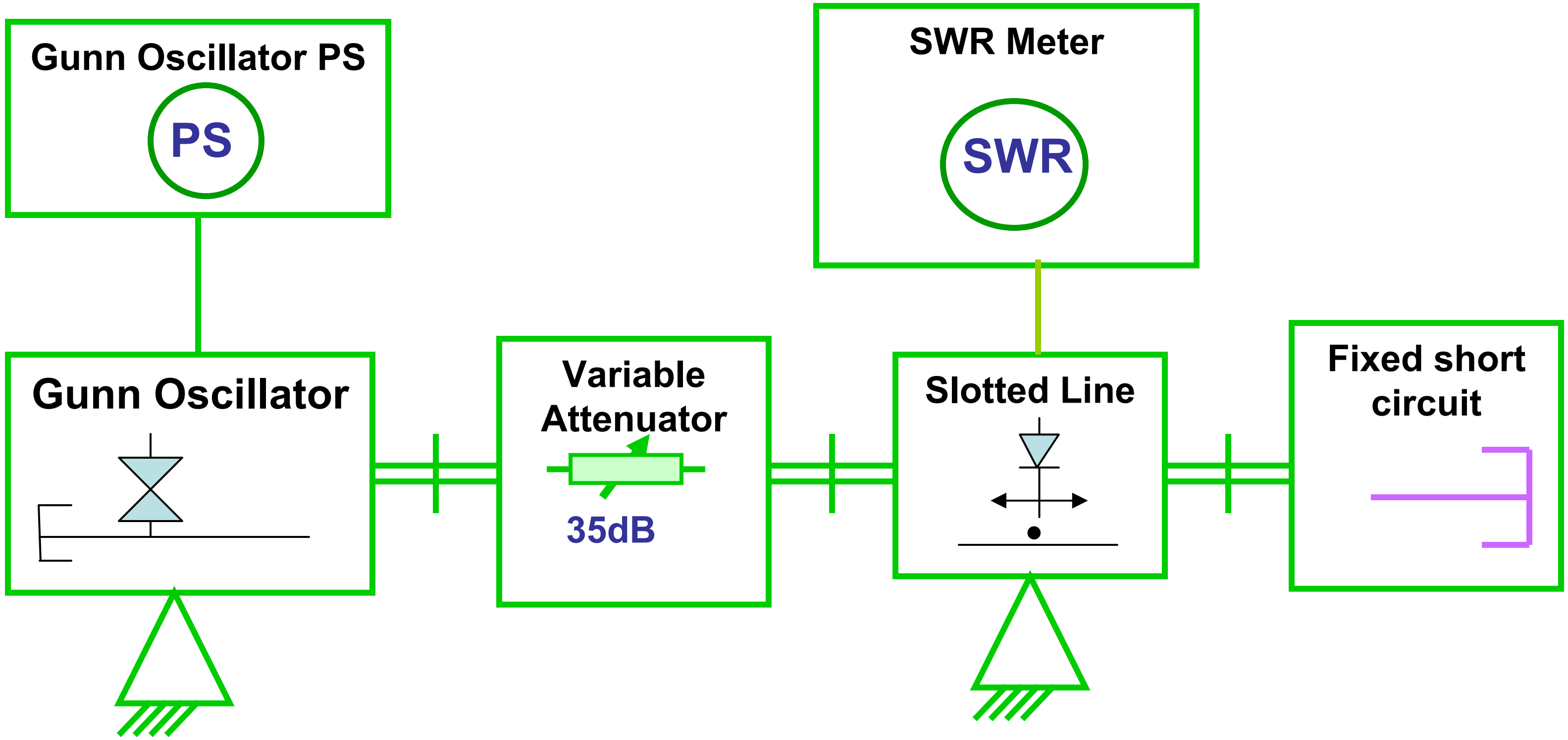
- Transfer oscillator down-conversion: use PLL to relate the harmonic relationship between the low frequency oscillator and the input microwave signal > 40GHz



Harmonic heterodyne: use mixer to harmonically down convert the input microwave signal <20GHz



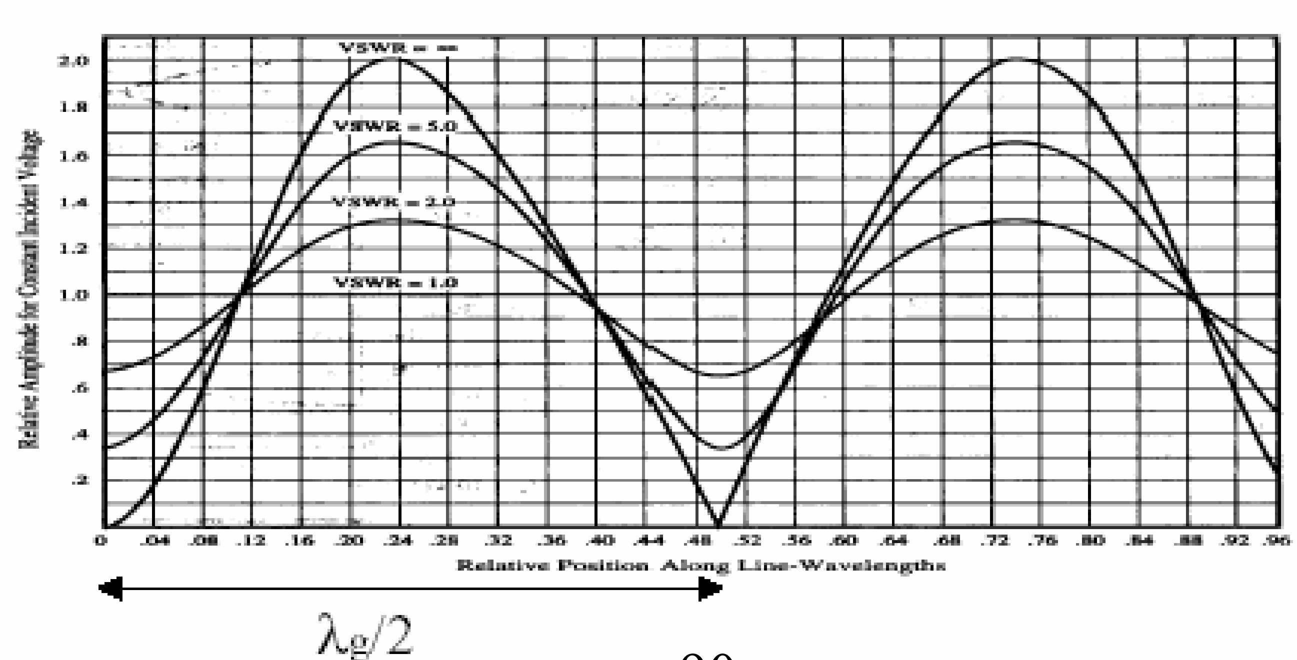
Wavelength measurement approach



$$k_c = \frac{2\pi}{\lambda_c}, \lambda_c = 2a, \beta = \frac{2\pi}{\lambda_g} = \sqrt{k^2 - k_c^2} = \sqrt{\left(\frac{2\pi}{\lambda}\right)^2 - \left(\frac{2\pi}{\lambda_c}\right)^2}$$

Measure $$\lambda_g \rightarrow f = c\sqrt{\left(\frac{1}{\lambda_g}\right)^2 + \left(\frac{1}{2a}\right)^2}$$

Distance between two adjacent minima is 1.9cm in a WR-90 waveguide.



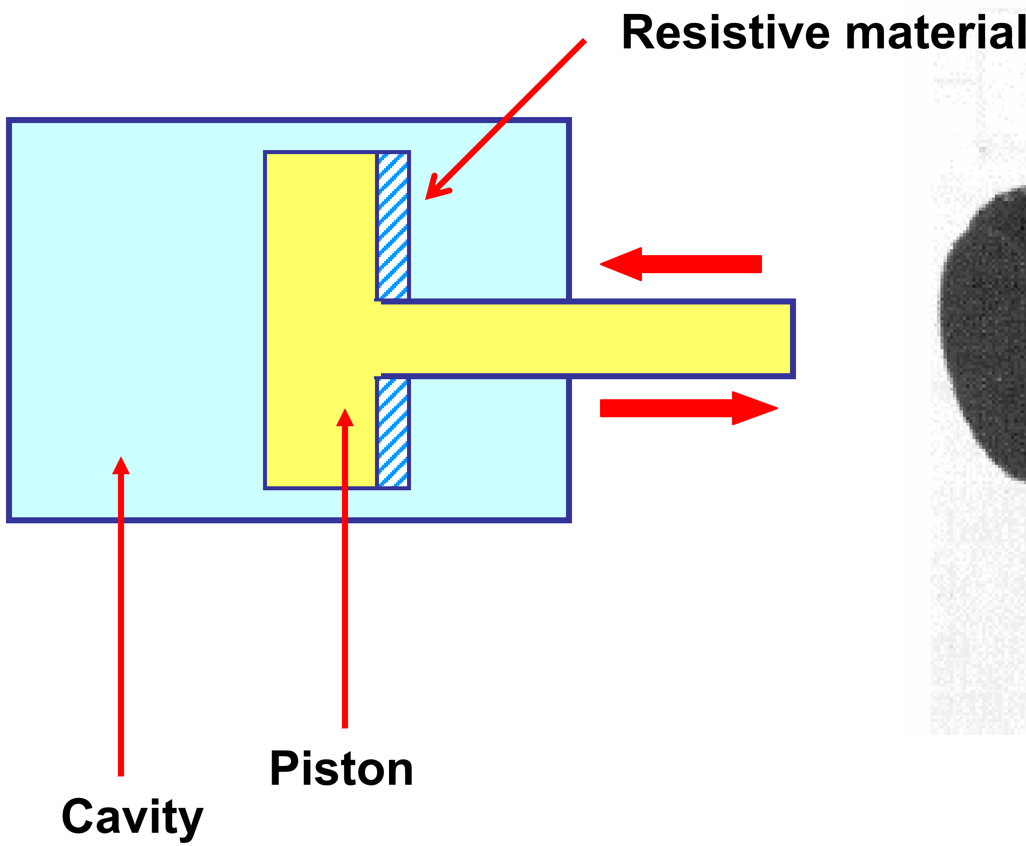
$$\lambda_g = 2\times 1.9cm = 3.8cm, \;\; a = \frac{90}{100}\times 2.54cm = 2.29cm$$

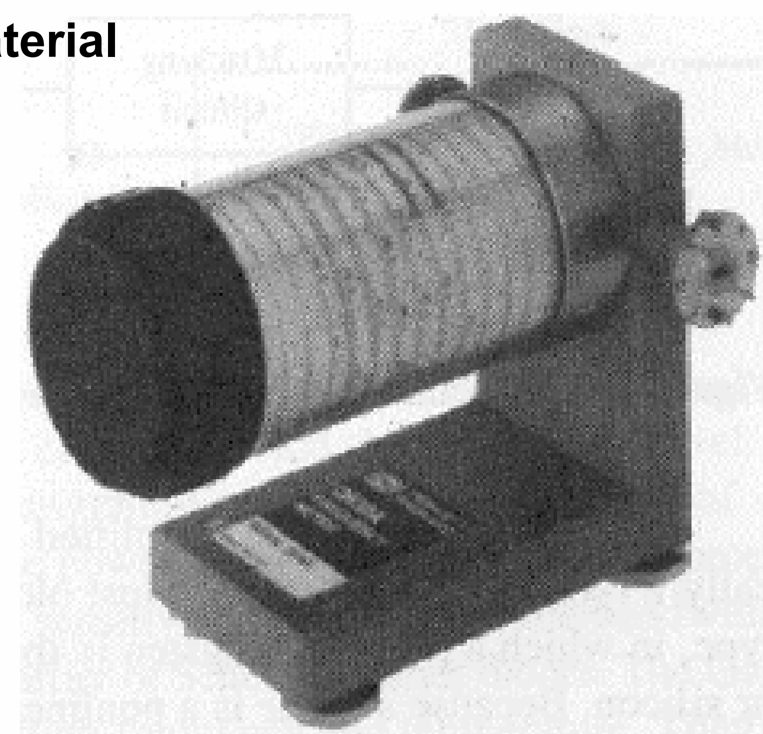
$$f = c\sqrt{\left(\frac{1}{\lambda_g}\right)^2 + \left(\frac{1}{2a}\right)^2}$$

$$= 3\times 10^{10}\,cm/sec\sqrt{\left(\frac{1}{3.8cm}\right)^2 + \left(\frac{1}{2\times 2.29cm}\right)^2} = 10.26\,GHz$$

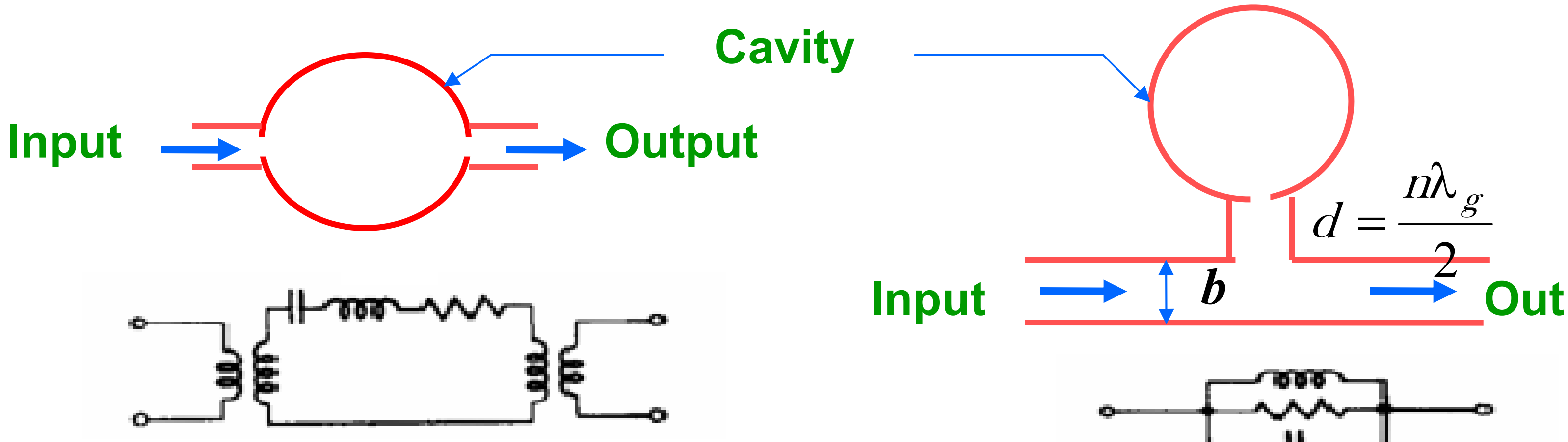
Wavemeter method

- **Wavemeter structure**



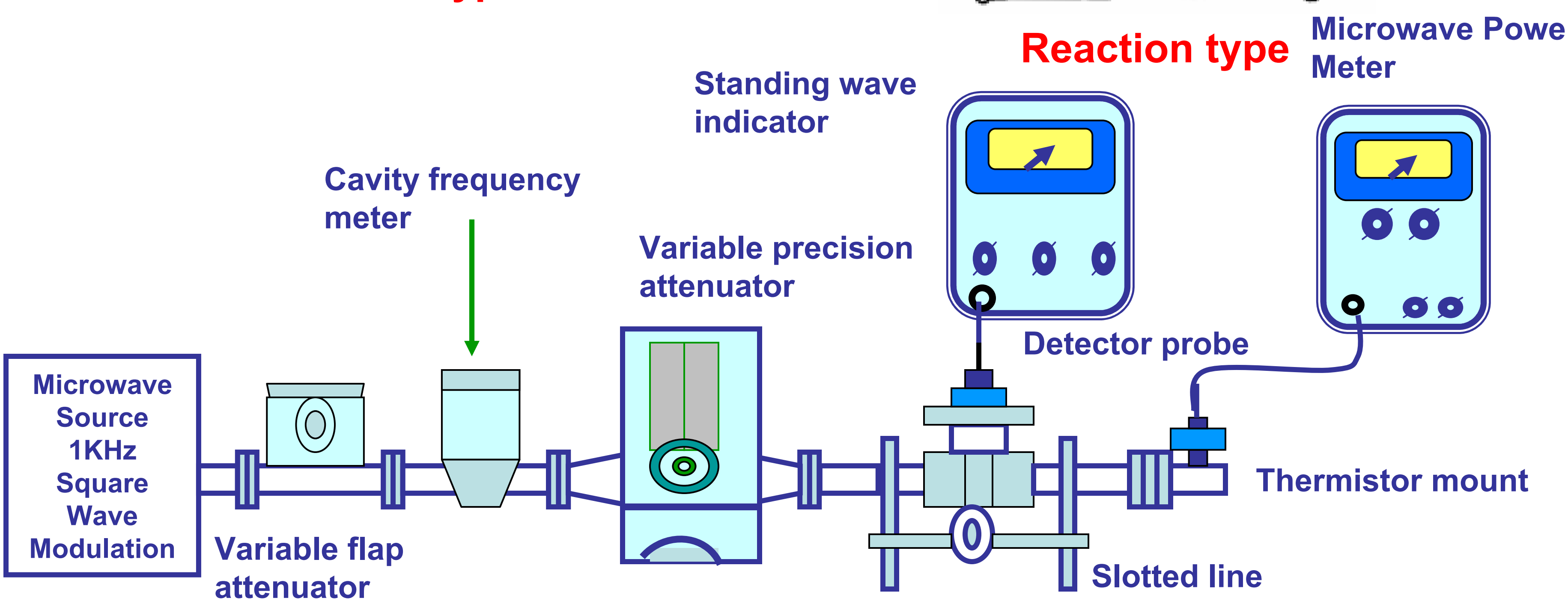


Operating principle



Transmission type

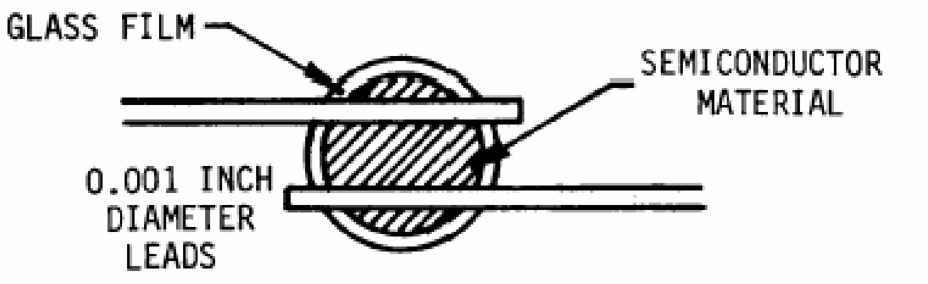
Reaction type



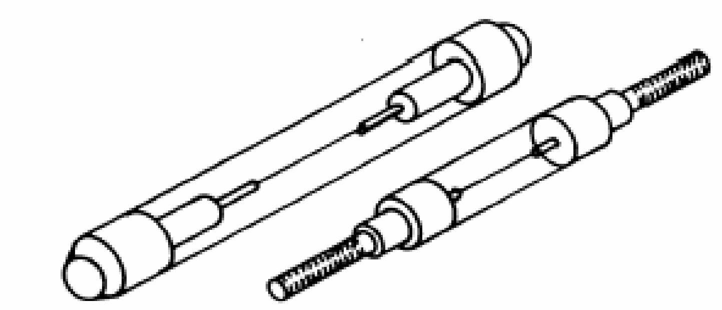
Detection devices

Power detector: bolometer (thermistor and barretter), thermocouple voltage detector: crystal detector, Schottky barrier diode, GaAs barrier diode

Thermistor: a metallic-oxide component with a negative temperature coefficient of resistance



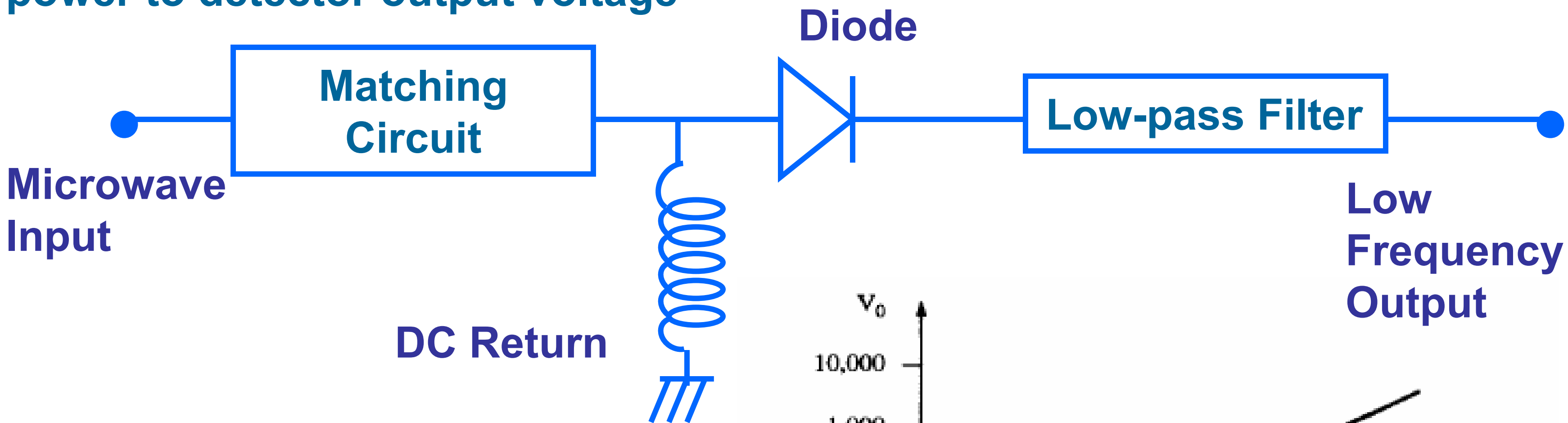
Barretter: a short length of platinum or tungsten wire with a positive temperature coefficient of resistance

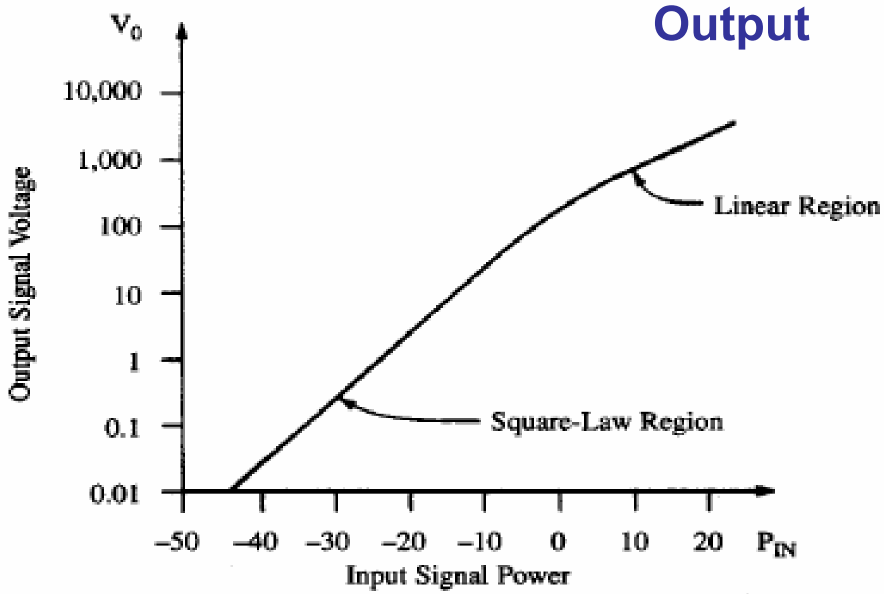


Detection devices

Thermocouple: a pair of dissimilar metal (Sb-Bi) wires joined at one end (sensing end) and terminated at the other end (reference end). The difference in temperature produces a proportional voltage.

Crystal detector: use the diode square-law to convert input microwave power to detector output voltage





DC return is as a ground for diode and an RF choke.

Detection devices

Schottky barrier or GaAs barrier diode: high sensitivity noise equivalent power (NEP): the required input power to produce, in 1Hz bandwidth, an output SNR = 1 tangential sensitivity (TSS): the lowest detectable microwave signal power

$$NEP = \frac{TSS}{2.5\sqrt{\Delta f}}, \Delta f \; : Vedio\ Bandwidth$$

Characteristics	Crystals	Barretters	Thermistors
Response Time	Extremely fast	$\approx 350\ \mu s$	≈ 1 sec
Square-law Response	$\approx 10\ \mu W$	$\approx 200\ \mu W$	$\approx 200\ \mu W$
Resistance to Burnout	Determined by design	≈ 12 mW	≈ 25 mW
Resistance to Shock	Poor	Fair	Good
Temperature Coefficient	None	Positive	Negative
Minimum Discernable Signal	$1.8 \times 10^{-6}\ \mu W$	$1.0 \times 10^{-4}\ \mu W$	$1.0 \times 10^{-4}\ \mu W$
Method of Operation	Rectifies Voltage	Absorbs EM energy	Absorbs EM energy

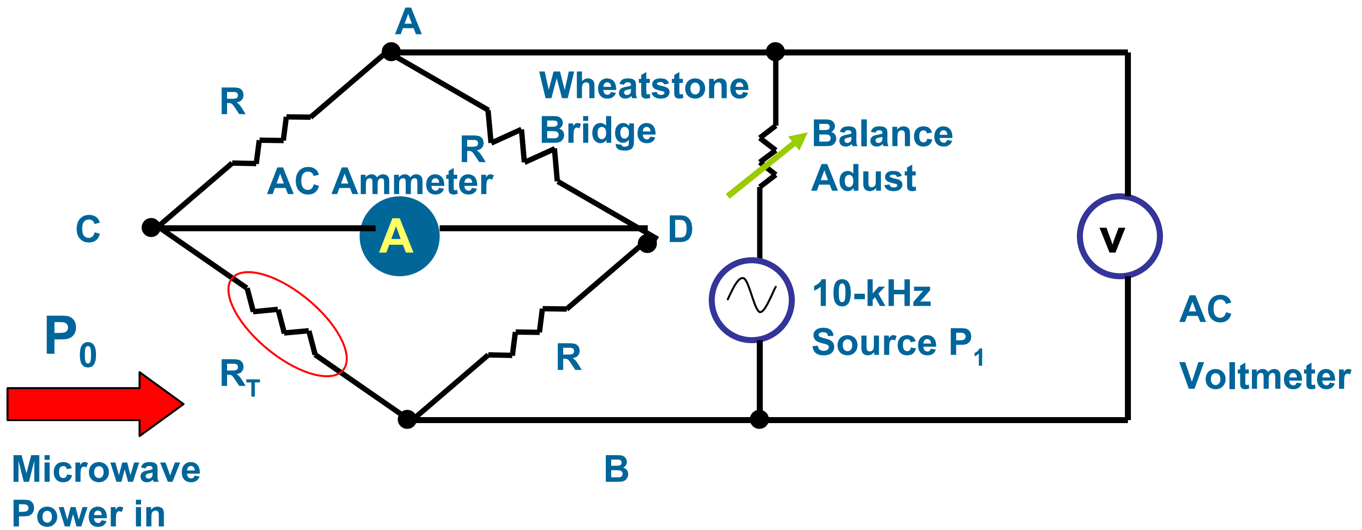
Power Measurements

Difficulty in measuring voltage or current at microwave frequencies
$\rightarrow$ power measurement simpler and more precise

Power range: low power <0dBm, medium power 0dBm~40dBm, high power >40dBm

power detector sensitivity: diode ~-70dm, thermistor ~-20dBm

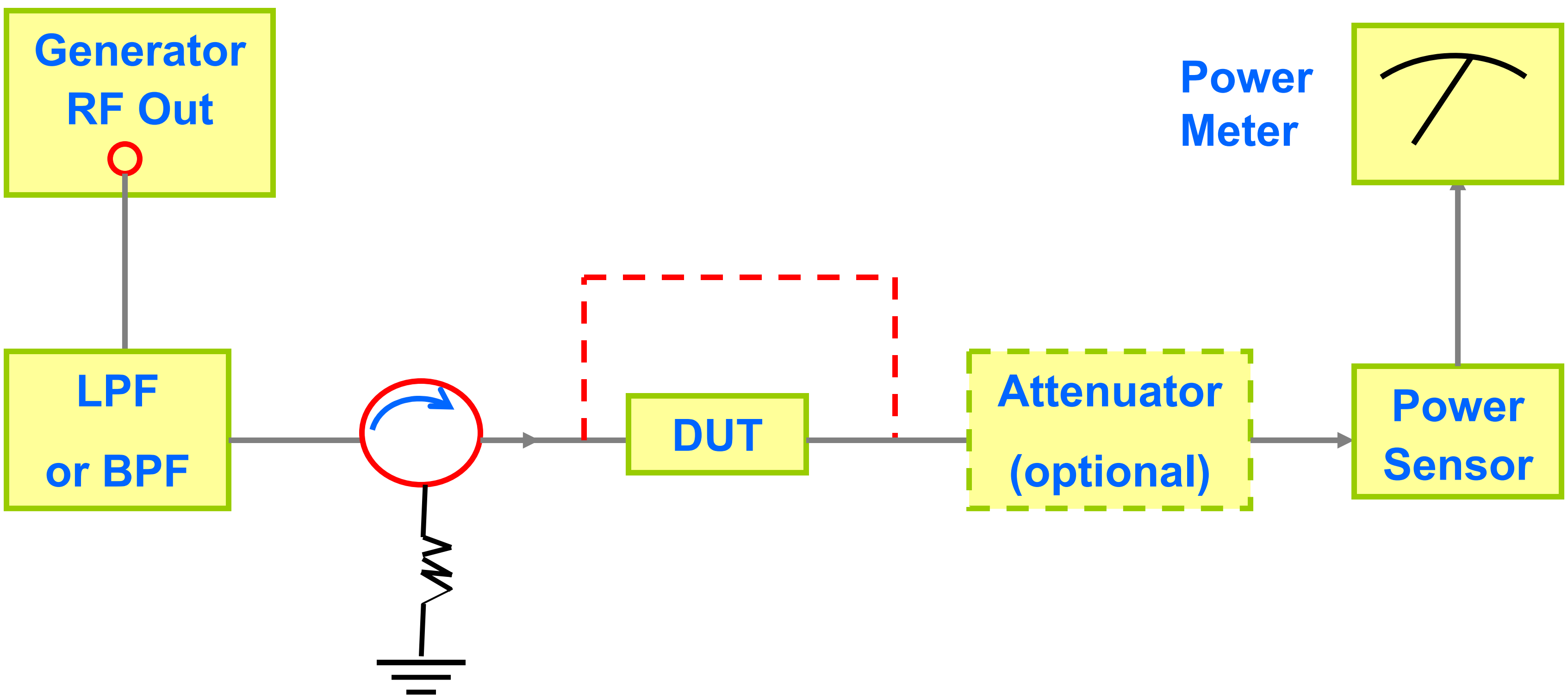
Thermistor power meter



Power measurement arrangement

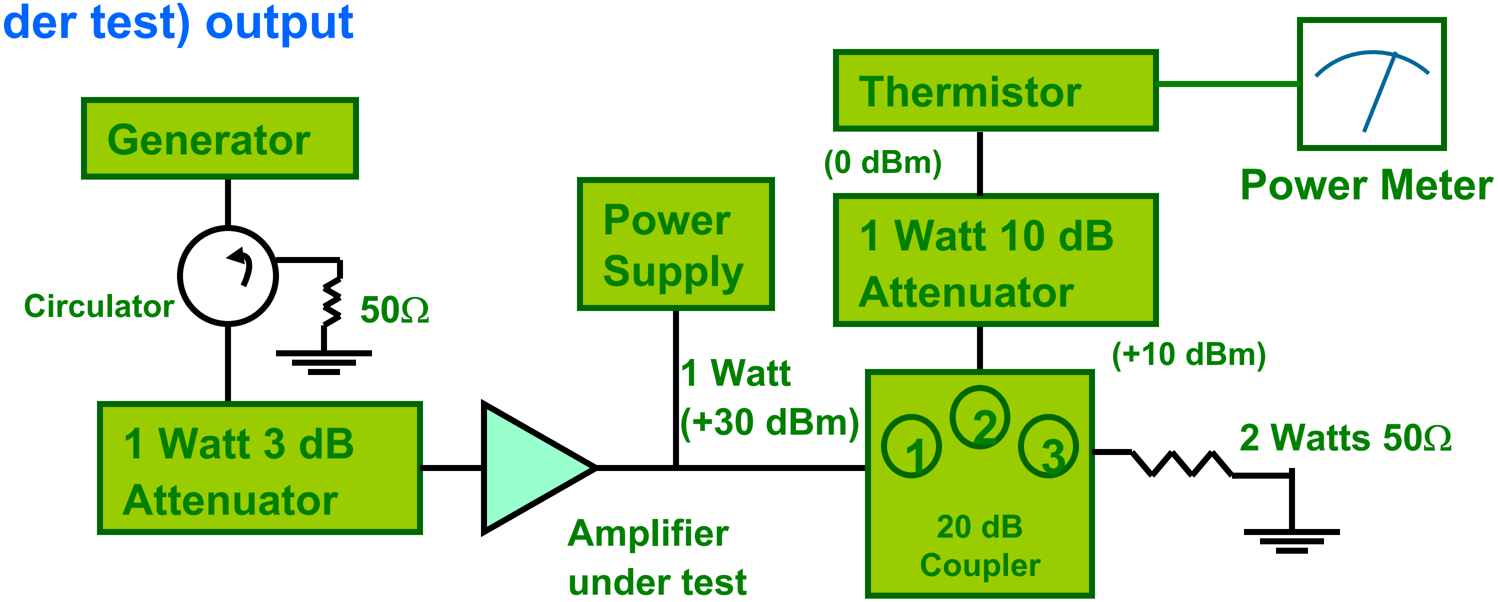
- Low power case

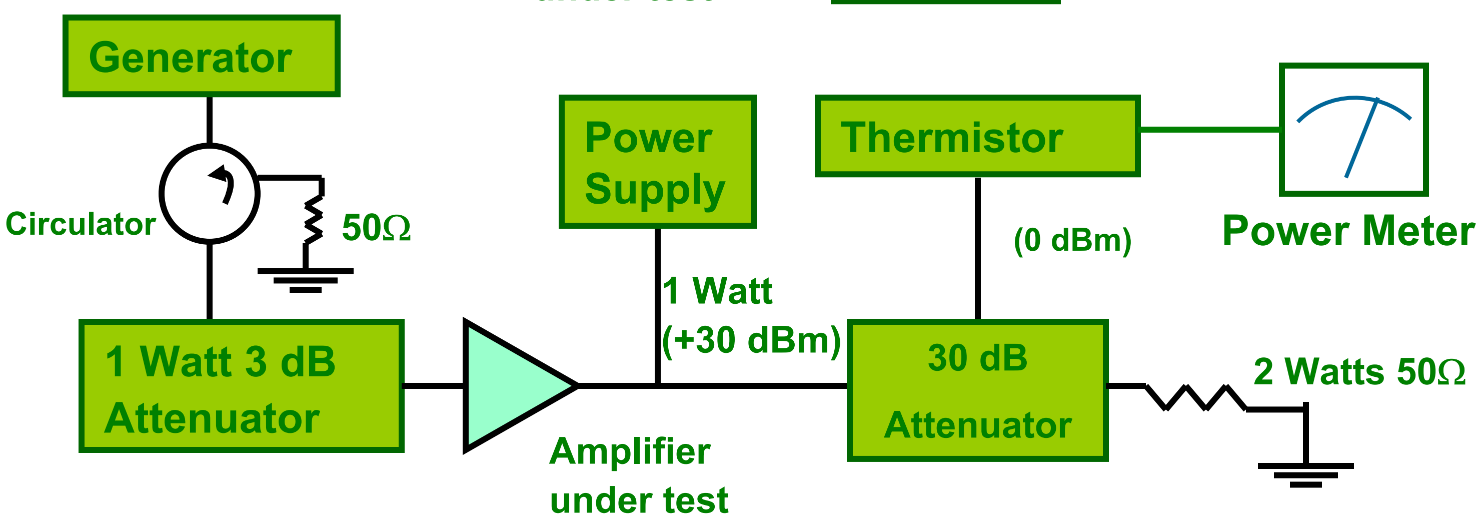
Consider desired frequency spectrum, circuit mismatch, sensor mismatch, sensor safe margin, accuracy, calibration



Power measurement arrangement

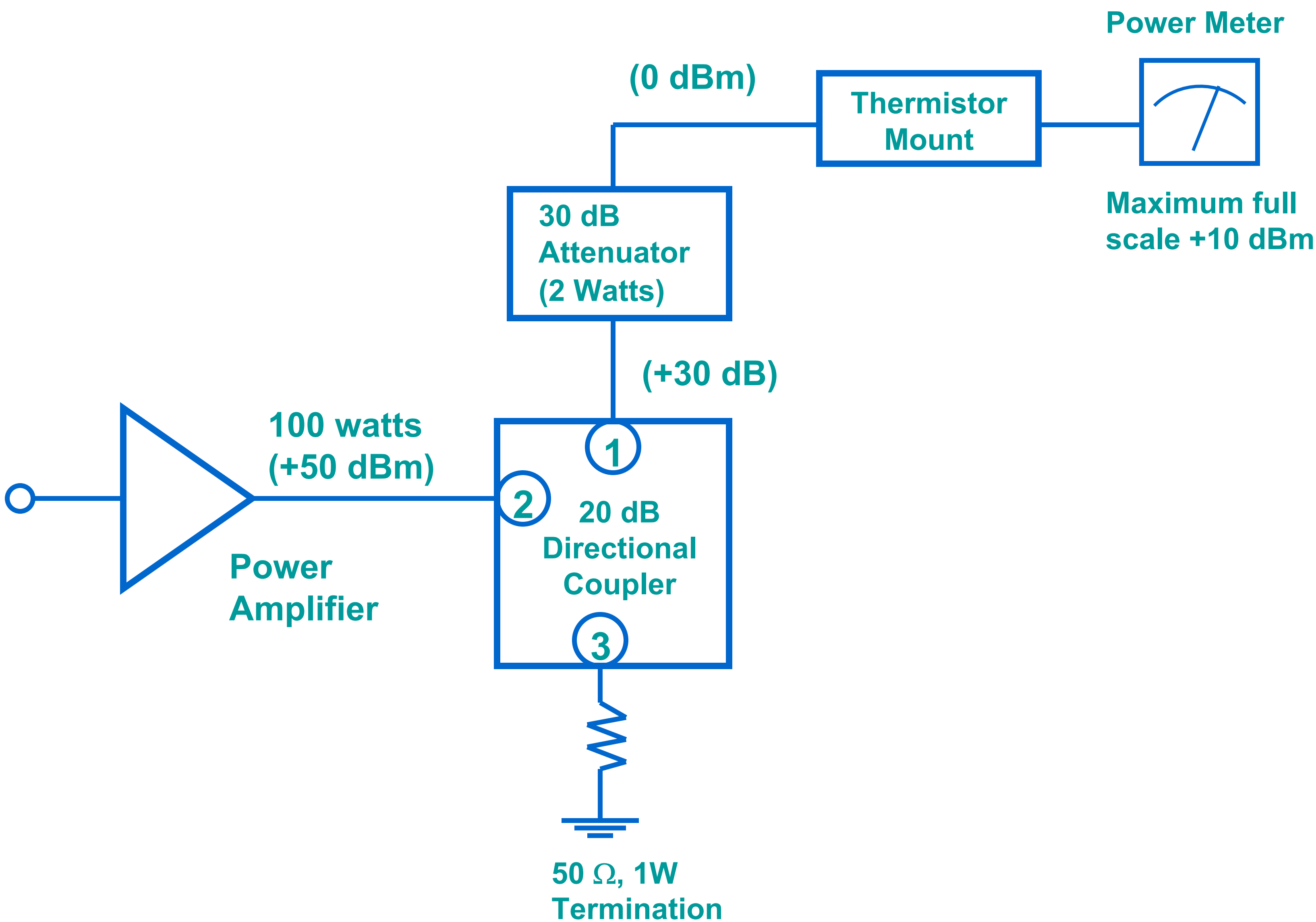
Medium power case: use directional coupler or attenuator at the DUT (device under test) output





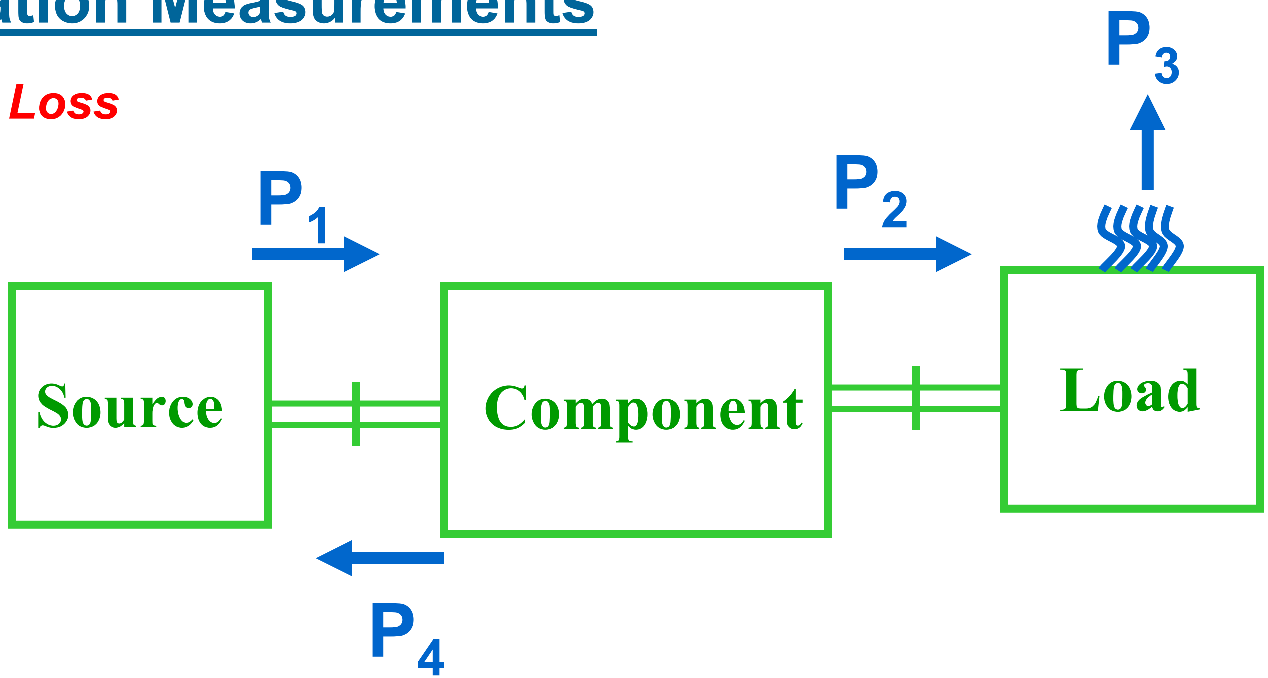
Power measurement arrangement

High power case: use directional coupler in reverse direction



Attenuation Measurements

Insertion Loss



P1: power to the load without DUT
P2: power to the load after inserting DUT
P3: power dissipated inside DUT
P4: power reflected from DUT

$$IL_{dB} = 10\,log\frac{P_1}{P_2} = P_{1(dBm)} - P_{2(dBm)}$$

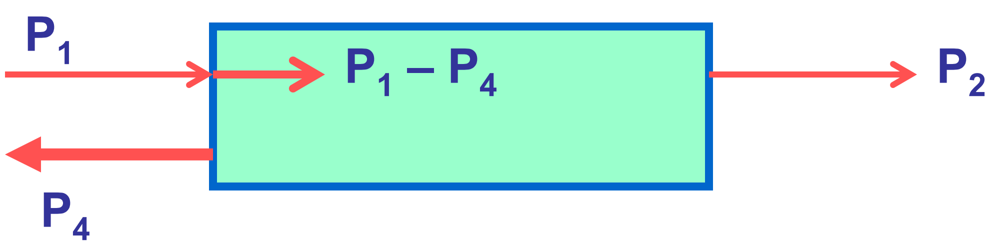
If Γ: DUT reflection coefficient and T: DUT transmission coefficient,

$$IL_{dB} = -10\,log|T|^2 = -10\,log|T|^2 \frac{1-|\Gamma|^2}{1-|\Gamma|^2}$$

$$= -10\,log\left(1-|\Gamma|^2\right) - 10\,log\frac{|T|^2}{1-|\Gamma|^2}$$

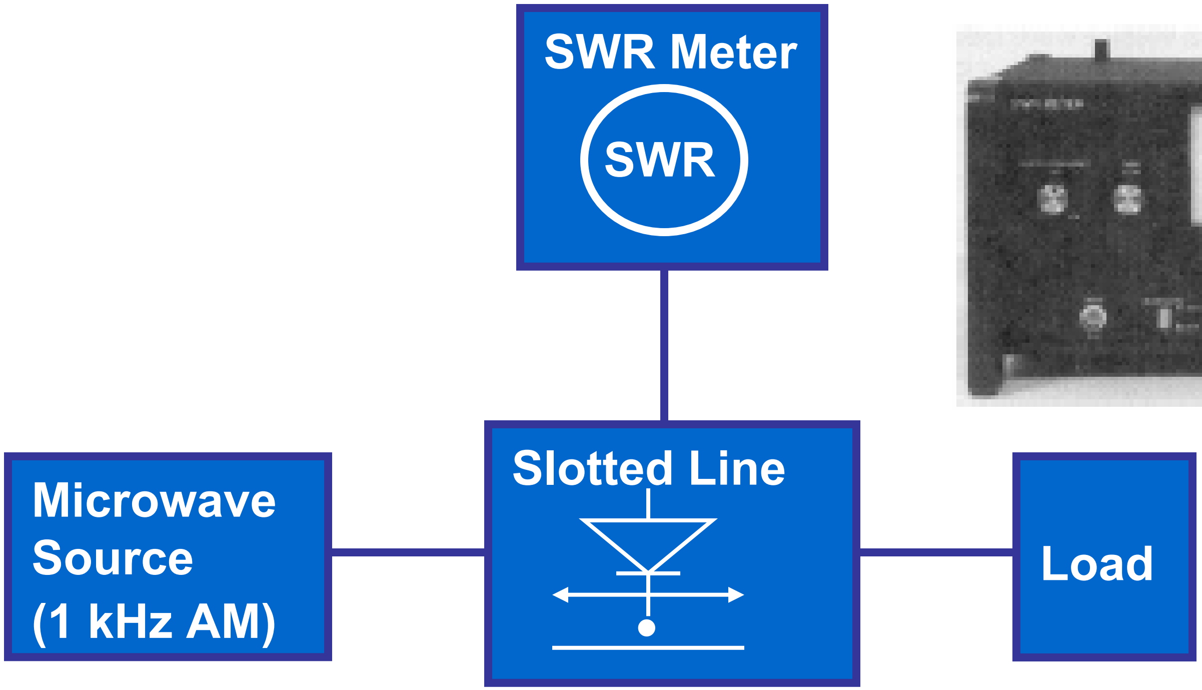
$$= -10\,log\frac{P_1 - P_4}{P_1} - 10\,log\frac{P_2}{P_1 - P_4}$$

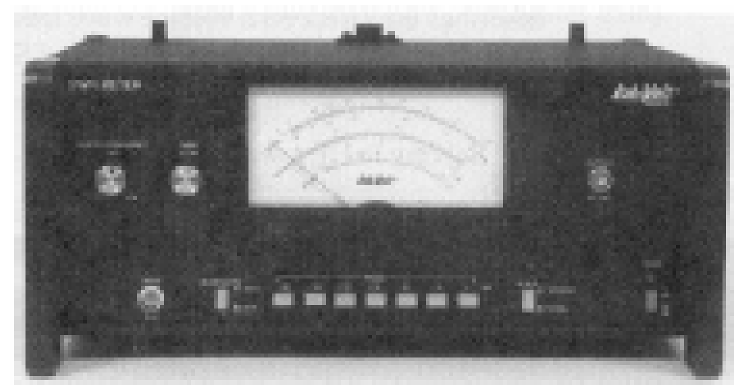
= loss due to reflection + loss due to transmission



Insertion loss is the characteristics of DUT itself. As input port and output ports are matched, IL= attenuation.

VSWR measurements





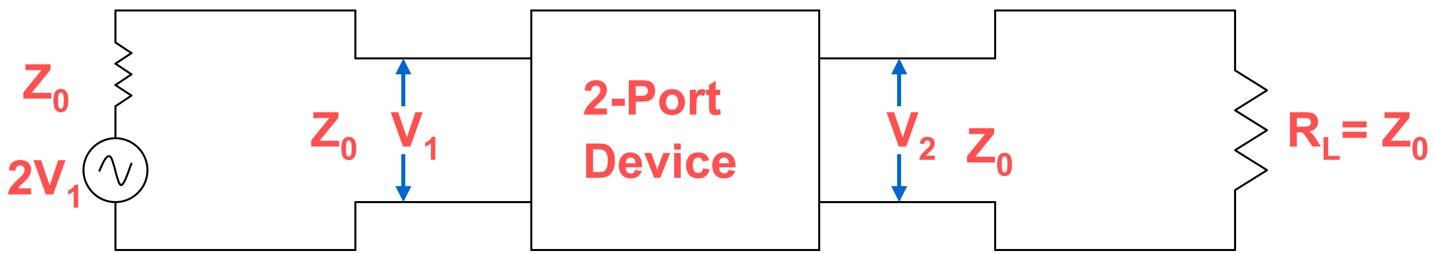
If E probe penetrates too far into the slotted line, → disturb the field distribution and detected signal too strong to drive the detector out of its square-law region.

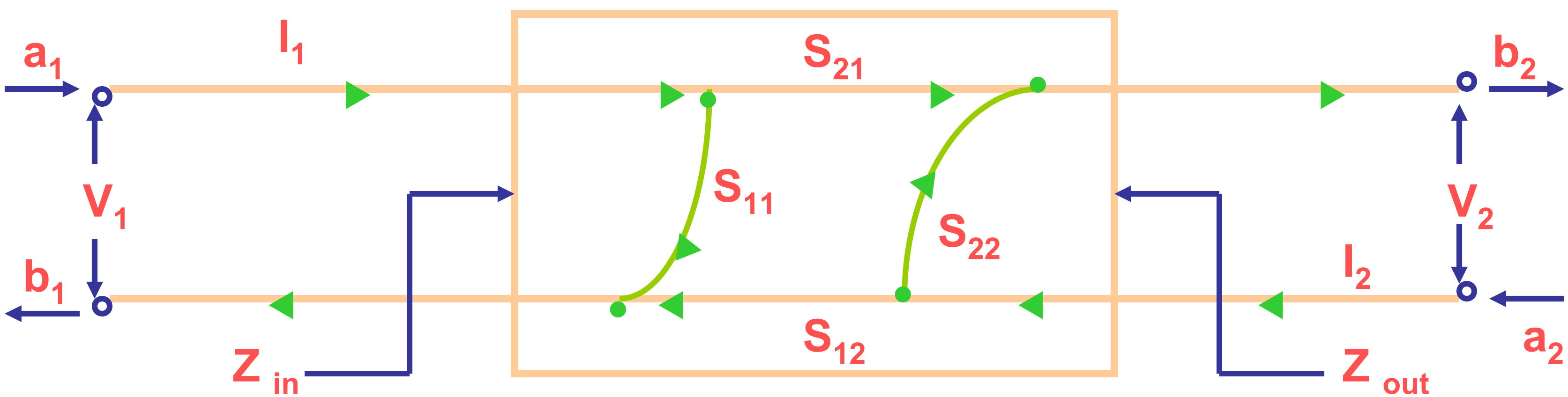
S- Parameters

Problems to use Z- , Y- or H- parameters in microwave circuits

- Difficult in defining voltage and current for non-TEM lines
- No equipment available to measure voltage and current in complex value as oscilloscope
- Difficult to make open and short circuits over broadband
- Active devices not stable as terminated with open or short circuit.

S-parameters of a two-port network





Definition of S- Parameters

$a_1 = V_1^+ / \sqrt{Z_0}$: incident (power) wave at port 1

$b_1 = V_1^- / \sqrt{Z_0}$: reflected (power) wave at port 1

$a_2 = V_2^+ / \sqrt{Z_0}$: incident (power) wave at port 2

$b_2 = V_2^- / \sqrt{Z_0}$: reflected (power) wave at port 2

$$V_1 = V_1^+ + V_1^-, V_2 = V_2^+ + V_2^-, I_1 = \frac{V_1^+}{Z_0} - \frac{V_1^-}{Z_0}, I_2 = \frac{V_2^+}{Z_0} - \frac{V_2^-}{Z_0}$$

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}, S_{ij} = \left. \frac{b_i}{a_j} \right|_{a_i = 0, k \neq j} = \left. \frac{V_i^-}{V_j^+} \right|_{V_k^+ = 0, k \neq j}$$

Incident power to port *i*: $P_i = \frac{1}{2} \Re e \left\{ V_i I_i^* \right\} = \frac{1}{2} |a_i|^2 - \frac{1}{2} |b_i|^2$

Properties of S- Parameters

$$S_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0}$$: reflection coefficient at port 1 with port 2 matched

$$S_{21} = \left.\frac{b_2}{a_1}\right|_{a_2=0}$$: forward transmission coefficient with port 2 matched

$$S_{12} = \left.\frac{b_1}{a_2}\right|_{a_1=0}$$: reversed transmission coefficient with port 1 matched

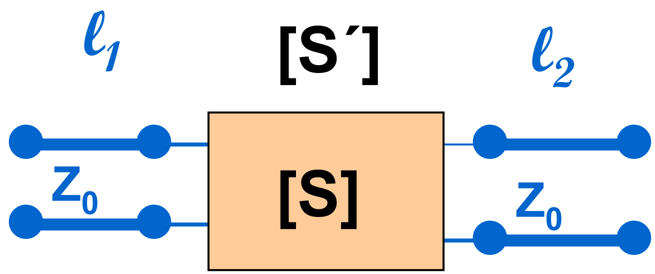
$$S_{22} = \left.\frac{b_2}{a_2}\right|_{a_1=0}$$: reflection coefficient at port 2 with port 1 matched

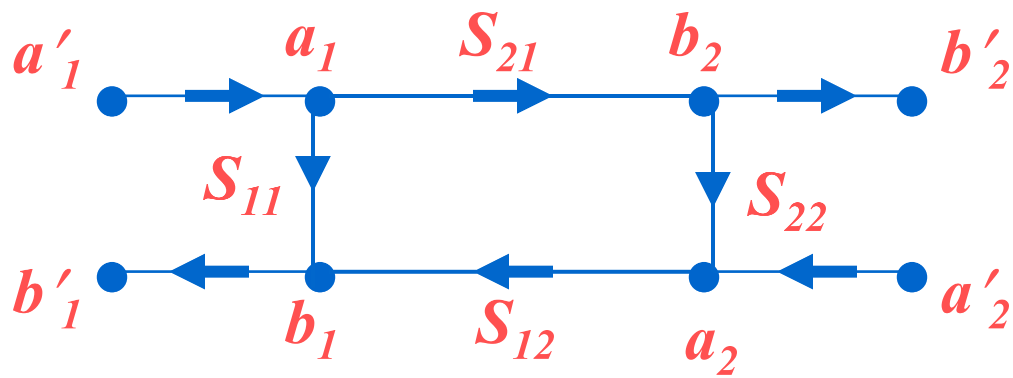
IL or power gain from port 1 to port 2 $= -10\,log\left|S_{21}\right|^2$

IL or power gain from port 2 to port 1 $= -10\,log\left|S_{12}\right|^2$

RL at port 1 or port 2 $= -10\,log\left|S_{11}\right|^2$ or $= -10\,log\left|S_{22}\right|^2$

Properties of S- Parameters





$$S'_{11} = S_{11}e^{-j2\beta\ell_1}, S'_{21} = S_{21}e^{-j2\beta(\ell_1+\ell_2)}$$

$$S'_{12} = S_{12}e^{-j2\beta(\ell_1+\ell_2)}, S'_{22} = S_{22}e^{-j2\beta\ell_2}$$

$$b_1 = a_1S_{11} + a_2S_{12}$$

$$b_2 = a_1S_{21} + a_2S_{22}$$

Reasons to use S-matrix in microwave circuit

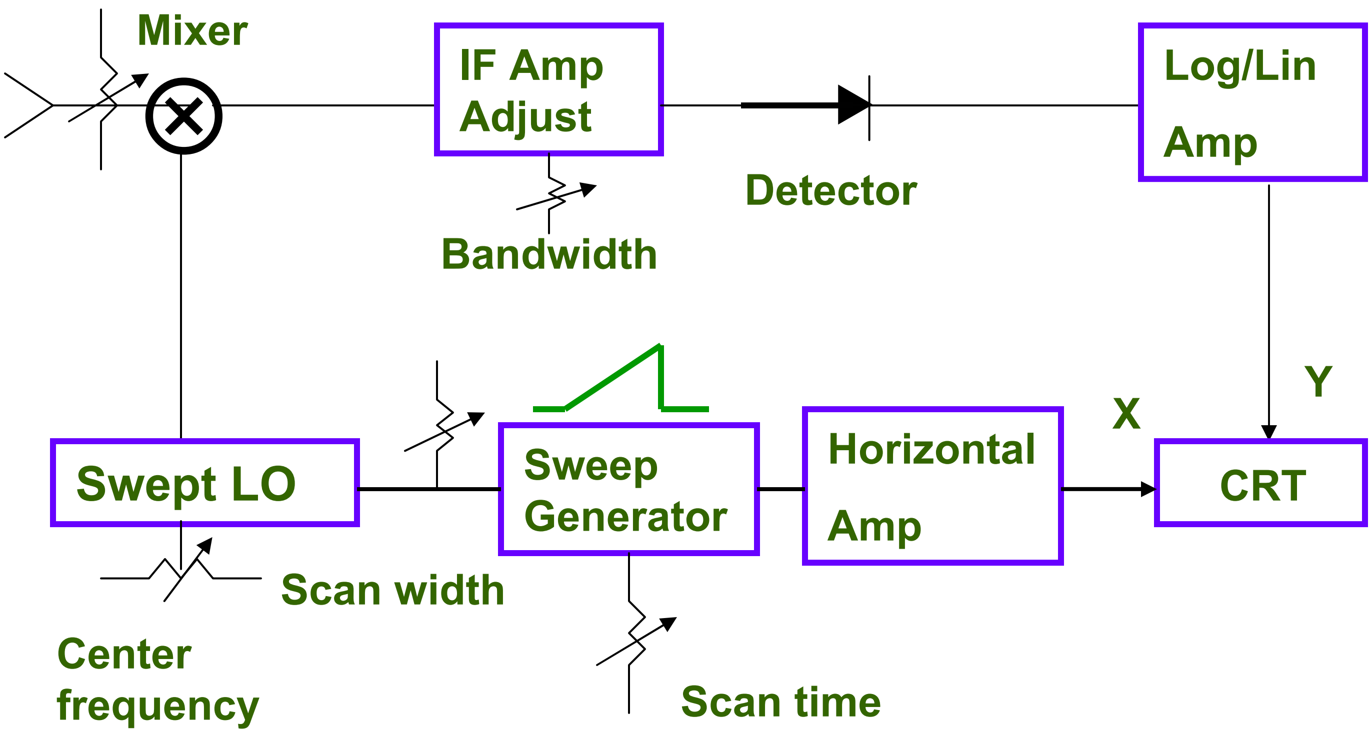
(1) matched load available in broadband application
(2) measurable quantity in terms of incident, reflected and transmitted waves
(3) termination with Z_0 causes no oscillation
(4) convenient to use in the microwave network analysis

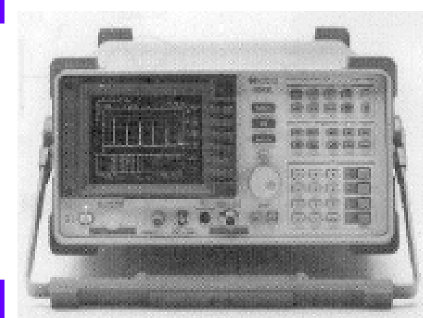
Microwave analyzers

Spectrum analyzer

Purpose: measure microwave signal spectrum, can also be used to measure frequency, rms voltage, power, distortion, noise power, amplitude modulation, frequency modulation, spectral purity,...

Operating principle

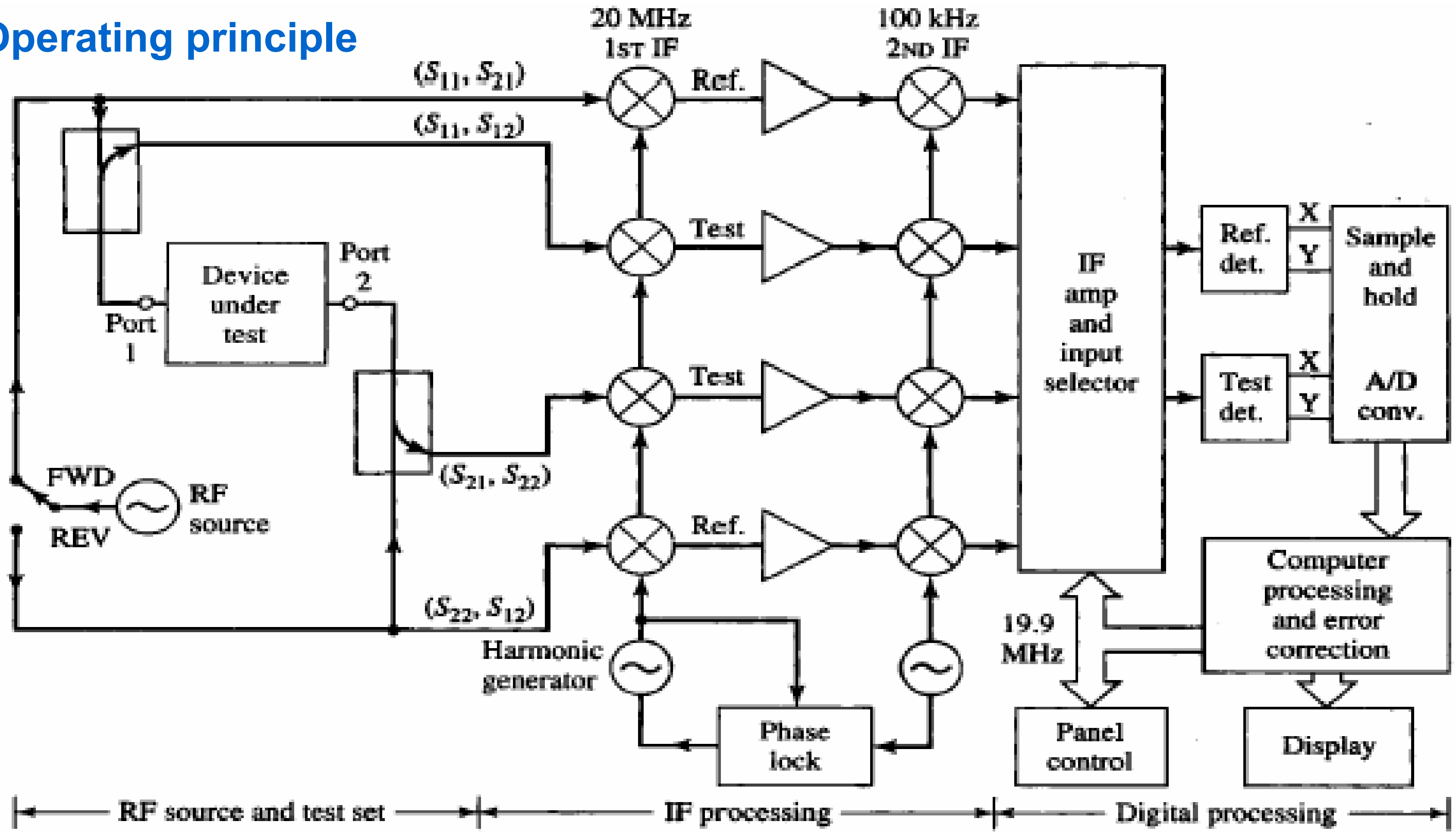




Network analyzer

Purpose: measure two-port S-parameter of a microwave device or network, can also be used to measure VSWR, return loss, group delay, input impedance, antenna pattern, dielectric constant,….

Operating principle



Scalar network analyzer measures the magnitude of two-port S-parameters.

Hp8510 vector network analyzer